17. LASER SYSTEMS

INTRODUCTION

Short-pulse laser systems will be instrumental components of the recirculating linac based synchrotron light source for ultrafast x-ray science. Both the machine operation and the scientific measurements at the beamline endstations will rely on short-pulse laser systems that must be integrated and synchronized at various levels of accuracy. The technical requirements for these lasers and how they integrate with the recirculating linac will be an important consideration in developing the conceptual design of the machine.

Lasers will play important roles in two areas of the machine operation. First, the overall machine timing will be determined by a modelocked laser oscillator (Master Oscillator). This laser will be the source of 1.3 GHz signals for the linac and 3.9 GHz signals for the superconducting rf deflecting cavities. Secondly, the linac photo-injector will require a dedicated laser system for driving the photo-cathode.

Lasers will also be widely employed at the beamline endstations, and each of these lasers will depend on the Master Oscillator for timing. The general scientific motivation for the hard x-ray component of the recirculating linac is to apply x-ray techniques in a time-resolved manner in order to investigate structural dynamics on the fundamental time scale on which atoms move, ~100 fs. The achievable temporal resolution will be dictated by the x-ray pulse duration, the laser pulse duration (at the beamline endstation) and the relative timing accuracy between laser and x-ray pulses. The beamline laser systems will be used for pump-probe measurements in which a laser pulse is used to initiate the dynamics of interest in a sample, and an x-ray pulse (delayed in time) is used to probe the transient sample response. Measurements will be typically done in a repetitive manner, and the dynamics mapped out as a function of the time delay between the excitation pulse and the probe pulse. Time-resolved x-ray measurements at the resolution limit (dictated by either the x-ray or laser pulse duration) will require absolute synchronization between the laser and x-ray pulses. The laser pulses must be delivered to the beamline endstations, and should provide the maximum flexibility to the beamline users in terms of pulse duration, tunability, pulse energy etc.

Figure 17-1 illustrates the general layout of the various laser systems for the recirculating linac. The overall timing for the machine is determined by the Master Oscillator which consists of a passively modelocked femtosecond laser oscillator coupled to a high-stability rf generator, and is described in Chapter 19-Synchronization. The Master Oscillator is the original source for the RF signals required for the linac as well as the original source of seed laser pulses for laser amplifiers at various beamline endstations. The photocathode drive consists of a second laser system (oscillator/amplifier combination) that is slaved to the Master Oscillator. Laser pulses from the Master Oscillator are distributed via an optical transport system to various beamlines. These pulses may be amplified directly at the beamline endstations in order to create laser pulses for sample excitation. Alternatively, seed pulses from the Master Oscillator may be effectively re-generated at the beamline endstations by using a separate modelocked femtosecond laser oscillator (synchronized to the Master Oscillator), followed by a power amplifier.

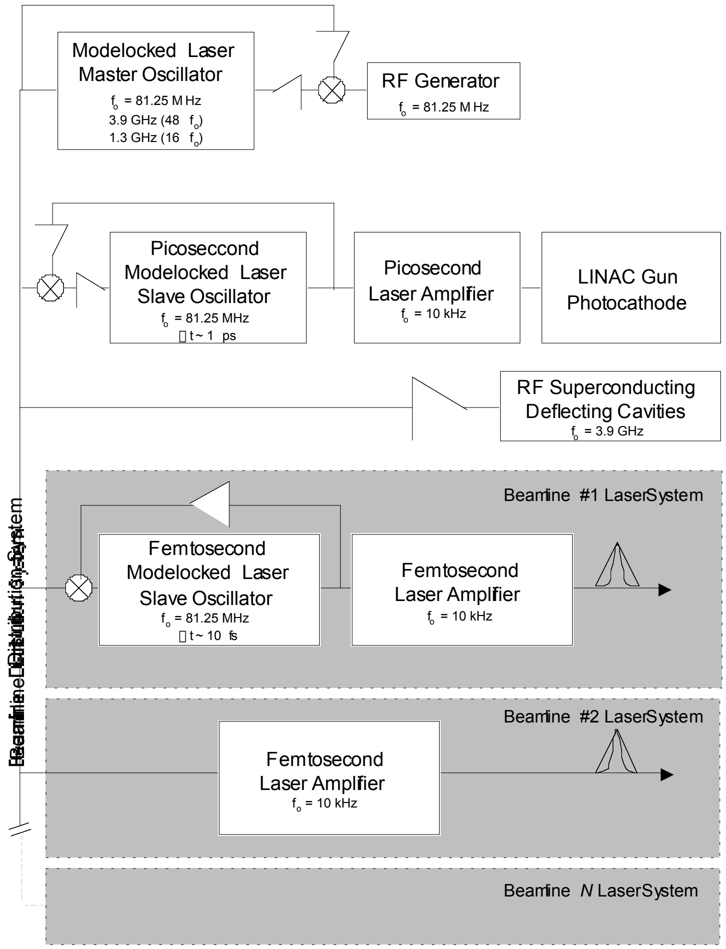

Figure 17-1 Schematic layout of the laser systems.

MASTER OSCILLATOR

The Master Oscillator provides the fundamental rf timing for the linac as well as femtosecond seed pulses for the beamline endstations. Thus, timing accuracy and phase stability are the most important criteria in the design of this component. The heart of the Master Oscillator is a passively modelocked femtosecond laser cavity providing optical pulses of less than 100 fs duration. In essence, this laser is a highly stable comb generator. By illuminating a photodiode with output pulses from this laser, one can generate rf harmonics extending from the fundamental oscillator frequency (cavity frequency = 81.25 MHz, round trip time = 12.3 ns), up to the bandwidth limit of the photodiode (which can extend well into the GHz range). Thus, this laser is a direct source for all the necessary rf signals for the linac. Because the laser is passively modelocked, the phase noise is substantially lower than that of conventional rf oscillators at frequencies above ~1 kHz. The dominant phase noise contribution for such lasers originates typically from mirror motion due to environmental acoustics as well as amplitude noise of the pump laser [1-3]. With advances in stable diode-pump sources, pump laser effects can be largely eliminated [e.g. Coherent Verdi and Spectra Physics Millenia models]. In addition, air turbulence effects are eliminated in hermetically sealed cavities, and in modelocked fiber lasers [4,5], both of which are available from commercial vendors [e.g. Coherent Vitesse and IMRA America Femtolite models]. Low frequency acoustic effects and long-term cavity drift can be effectively suppressed by locking the fundamental cavity frequency to a conventional high-stability generator [1]. This is accomplished by constructing a phase-locked loop as illustrated in Figure. 17-2, in which the laser cavity acts as a voltage-controlled oscillator by modulating the cavity length with a moving mirror attached to a piezoelectric transducer. Thus, a femtosecond laser phase-locked to a stable rf generator provides phase noise levels which match that of the rf generator at low frequencies (DC to ~1 kHz), and are substantially better at high frequencies.

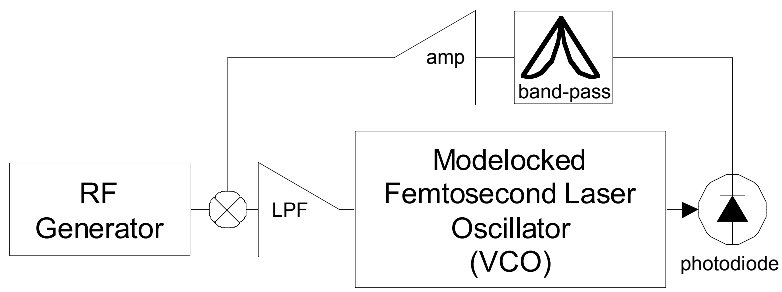

Figure 17-2 Master Oscillator.

Table 17-1 summarizes the essential characteristics of the Maser Oscillator laser. There are several important factors in determining the operating wavelength of this laser. First, most of the beamline laser systems are likely to be based on the solid-state laser media Ti:sapphire which has a peak gain near 800 nm. A Master Oscillator laser operating at this wavelength can provide femtosecond pulses for direct seeding of a Ti:sapphire amplifier at a beamline endstation. A second important consideration is the optical distribution system. This system must be extremely stable, particularly with respect to path length drift, (e.g. a path length drift of only 10 μm corresponds to a time shift of 30 fs). One approach is to use free-propagating beams and mirrors. In this case, pointing stability will require an active position feedback system and hermetically sealed (low vacuum) optical transport lines. A second approach is to use a fiber delivery system. With either approach, active monitoring of the path length stability is highly desirable. This may be accomplished by back-reflecting a portion of the pulses from the Master Oscillator to provide a path-length reference. Alternatively, a cw reference laser may be used with interferometric techniques to monitor and control the path length.

One advantage of an optical fiber delivery system is that it completely eliminates any pointing stability problem. However, in a fiber delivery system the nonlinear optical effects and pulse-stretching effects (group-velocity dispersion) must be adequately managed. Nonlinear optical effects might be managed by propagating sufficiently low pulse energies. Group velocity dispersion might be managed by using photonic bandgap fiber in which the group velocity dispersion is balanced by the modal dispersion [6]. Alternatively, by choosing a fiber laser operating at 1.55 μm as the Master Oscillator laser, one can take advantage of zero-dispersion fiber that is routinely used for telecommunications applications.

Table 17-1 General technical specifications for the Master Oscillator.

Master Oscillator Laser	
pulse duration (fs)	<100
wavelength (μm)	0.78 (1.55)
repetition rate (MHz)	81.25
average power (W)	~1
phase noise	<120 dBc/Hz

LINAC PHOTOCATHODE DRIVE LASER

The drive laser for the linac photocathode will be an independent system with a separate laser oscillator and amplifier. Although the required electron bunch duration from the photocathode gun is ~20 ps, the timing requirements for this system remain stringent as this will be the main source of timing jitter of the electron beam with respect to the master oscillator. Stability and reliability are extremely important in order to allow synchronization of pulses produced before the deflecting cavities, and in FEL's.

This Nd:YLF based laser system consists of a passively modelocked diode-pumped laser oscillator generating 10 ps pulses at 1.053 μm. Such oscillators are commercially available from Time-Bandwidth Products (model GE-100). The oscillator will be phase locked to the Master Oscillator (as illustrated in Fig. 17-3) with an rms jitter of less than 1 ps. Pulses from the oscillator will be amplified in a Nd:YLF based regenerative amplifier followed by frequency quadrupling to reach 0.26 μm. Suitable laser amplifiers based on Nd:YLF are commercially available from Positive Light Inc.

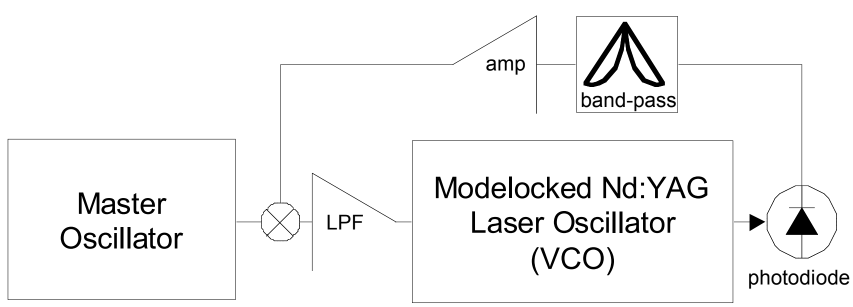

Figure 17-3 Phase locking of Master Oscillator to laser oscillator for photocathode driver.

Table 17-2 General technical specifications for the photocathode drive laser system.

Photocathode Drive Laser	
pulse duration (ps)	20
wavelength (μm)	1.053 (0.26)
repetition rate (kHz)	10
pulse energy @ 0.26 μm (mJ)	~0.1
rms jitter w.r.t Master Osc. (ps)	<1.0

BEAMLINE LASER SYSTEMS

It is anticipated that separate femtosecond laser systems will be required at each beamline for laser pump/x-ray probe experiments. Furthermore, the requirements for each system will vary depending on the specific research needs of each beamline. Nevertheless, the critical requirements for these laser systems are substantially the same. The most important requirements are timing accuracy and stability with respect to the femtosecond x-rays. Once the synchronization between the Master Oscillator and the femtosecond x-rays is established (as outlined above) the challenge for each beamline laser system is to maintain synchronism with the Master Oscillator. Part of this will rely on the stability of the optical distribution system (either free-space propagation or fiber based) which will deliver a 81.25 MHz train of (low energy, ~nJ/pulse) femtosecond optical pulses to each endstation.

Depending on the laser requirements for individual beamline, the laser system may take one of two forms (as illustrated in Figure. 17-1). In the simplest case, the pulses from the Master Oscillator may be use to directly seed a chirped-pulse amplifier (in which the seed pulses are temporally stretched, amplified, and re-compressed). The more general case requires active synchronization of a second laser oscillator (located at the beamline endstation) to the Master Oscillator. This approach is technically more challenging, but considerably more flexible since it is largely independent of the operating wavelength or pulse energy delivered by the Master Oscillator. Synchronization of two independent passively modelocked oscillators has been demonstrated with rms jitter of less than 1 fs (over the 1 Hz-160 Hz frequency range) [2]. Anticipated advances in laser oscillator design and synchronization stability suggest that even better performance will be achieved in the future. The significant advantage of this approach is that it de-couples the requirements of the beamline amplifiers from the Master Oscillator.

The beamline amplifiers may take many forms, possibly depending on the operating wavelength of the Master Oscillator. Nevertheless, amplifier systems are available from several commercial vendors. Standard chirped-pulse amplifiers based on Ti:sapphire are available from Positive Light Inc. and Coherent Inc. for example. Fiber based femtosecond amplifiers are available from IMRA America Inc. Coarse path length differences (>10 ns) between laser and x-ray pulses are easily compensated by amplifying the appropriate pulse from the Master Oscillator train. Finer path length differences are compensated using a conventional optical delay line. The general requirements of the beamline laser systems are outlined in Table 17-3. A pulse energy of ~1 mJ should be sufficient for most nonlinear optical techniques (continuum generation, harmonic mixing, parametric amplification etc.) which might be used to generate femtosecond pulses at the appropriate wavelength for sample excitation. Such amplifiers can be readily scaled to even higher pulse energies if necessary.

Table 17-3 General technical specifications for a typical beamline endstation laser system.

Beamline Laser (typical)	
pulse duration (fs)	<100
wavelength (μm)	0.8
repetition rate (kHz)	10
pulse energy (mJ)	>1.0
rms jitter w.r.t Master Osc. (fs)	<10

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